Excitation of the Fe XIV spectrum in the Sun, stars and Seyfert galaxies: reconciling theory, observations and experiment

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Introduction

- Observational background
- Modelling Seyfert spectra
- Theoretical work on the Fe XIV $^2P^o_{1/2}$ - $^2P^o_{3/2}$ transition
- Current state of theory
- Latest theory compared to experiment
- Thermally averaged collision strengths
- Summary

Observational background

- Fe optical forbidden lines, including Fe XIV were identified by Grotrian (1939) and Edlen (1943)
- Seen in the solar corona and in nova spectra in the 1930s
- In 1943 Seyfert identified several optical [Fe VII] lines in the spectra of the nuclei of some galaxies - to become known as Seyfert galaxies
- In the 1960s rocket borne spectrographs revealed the UV spectrum of the corona
- In 1968 Oke & Sargent report observations of a Seyfert Galaxy (NGC 4151) showing Fe XIV $\lambda 5303$ and Fe X $\lambda 6374$
- In the 1970s identifications of high ionization optical forbidden lines were also claimed in supernova remnants and binary stars

- More recently Oliva *et al* (1994) obtained this optical and near infrared spectrum of a nearby (4Mpc) Seyfert, the Circinus galaxy (A1409-65)
- The visible section clearly shows [Fe VII] $\lambda 6087$, [Fe X] $\lambda 6374$, [Fe XI] $\lambda 7892$ and [S VIII] $\lambda 9913$

458 E. Oliva et al.: Size and physical conditions of the coronal line region.

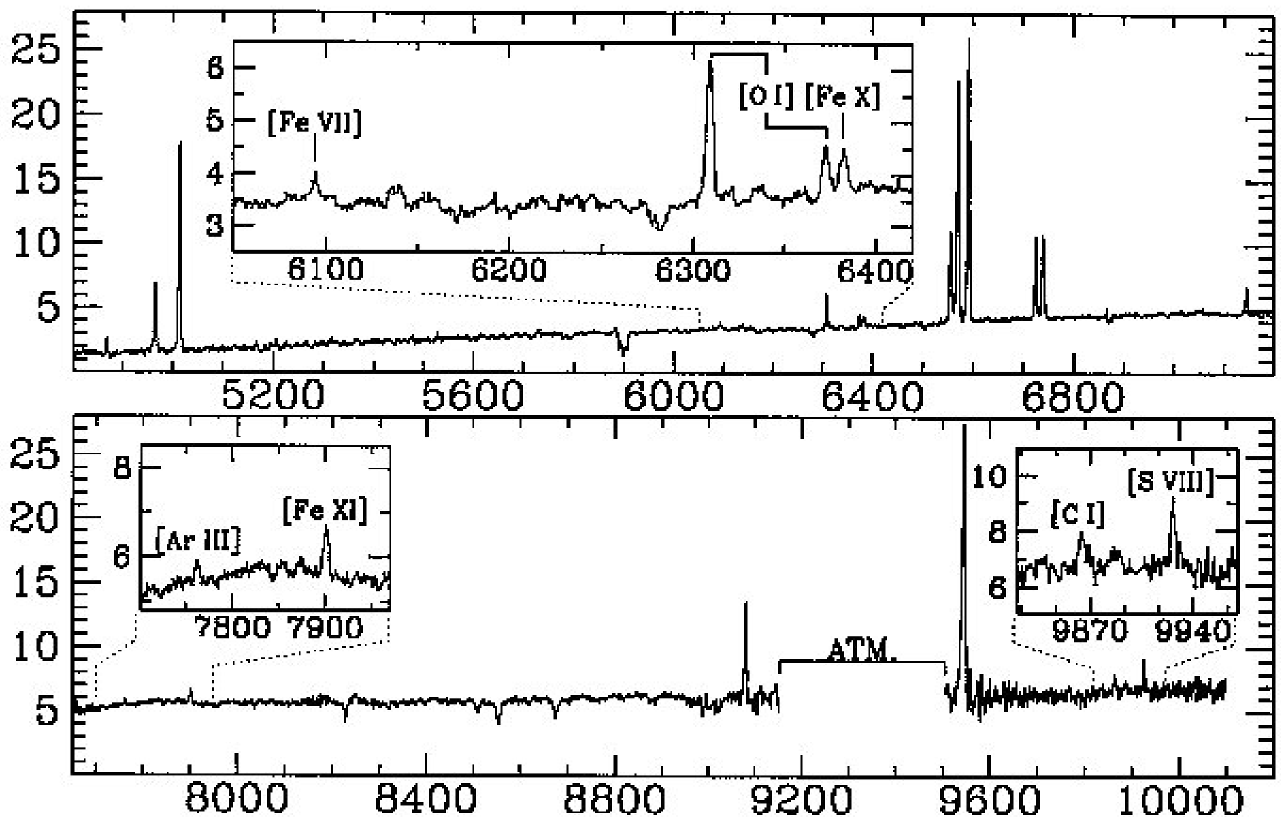
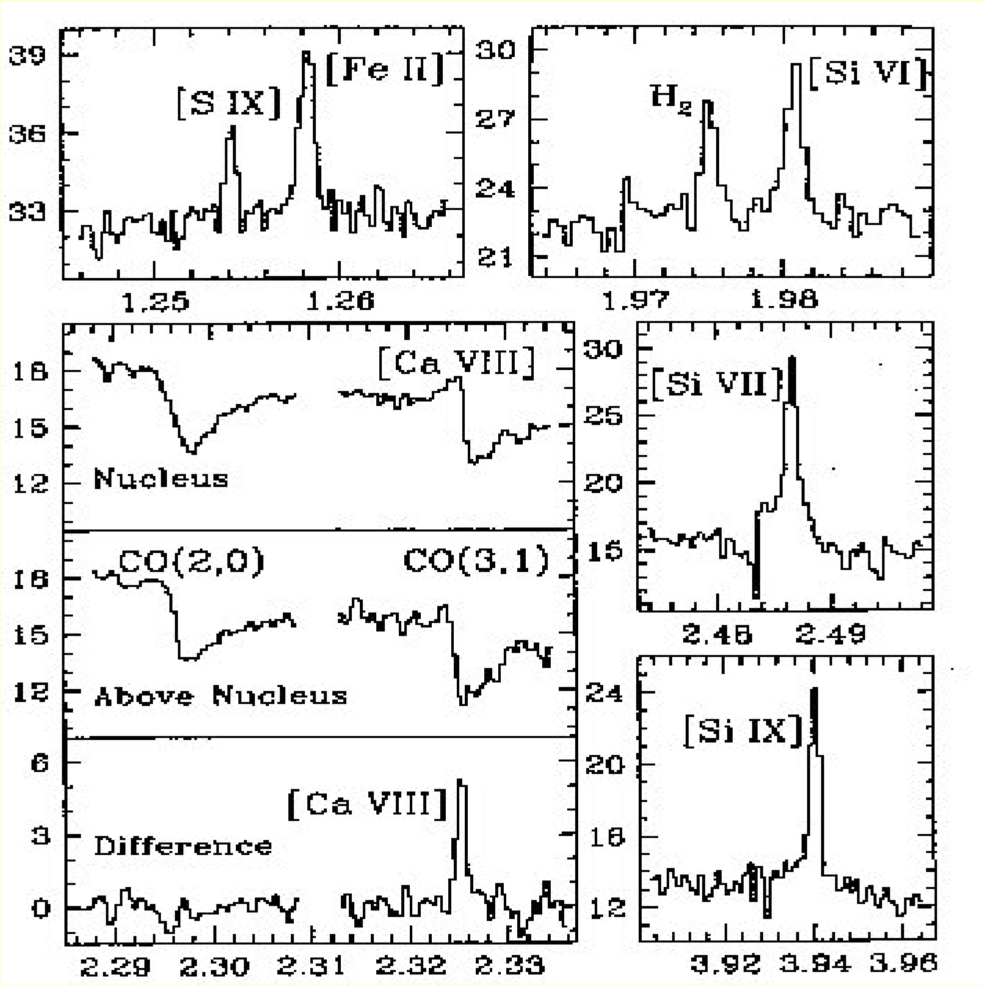


Fig. 1. EMMI spectrum of the central 1.5"x4.5" of the Circinus galaxy. Wavelengths are in Å and fluxes in units of 10^{-15} erg cm^{-2} s^{-1} Å^{-1}. 'ATM' is a region of bad atmospheric transmission

- while the near IR section clearly shows forbidden lines of Si VI $\lambda 1.963$, Si VII $\lambda 2.483$, Si IX $\lambda 3.935$, S IX $\lambda 1.252$ and Ca VIII $\lambda 2.321$



Modelling Seyfert spectra

- The interest in Seyfert spectra here relates to the physical conditions in which the forbidden lines are formed
- Oliva *et al* (1994) argue persuasively that the emitting gas is ionized by the hard UV continuum from the active galactic nucleus
- They model the spectrum using a continuum with a double power law spectrum. Elemental abundances are assumed solar

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Ratio	Obs	Oliva *et al* (1994)
[Fe X]/[S VIII]	2.4	3.2
[Fe XI]/[S VIII]	1.5	2.3
[Fe XIV]/[S VIII]	$<$2.4	0.77
[Fe VII]/[S VIII]	1.3	1.4
[Si VI]/[S VIII]	2.0	1.6
[Si VII]/[S VIII]	3.2	2.2
[S IX]/[S VIII]	1.0	1.0
[Ca VIII]/[S VIII]	1.5	0.59

- Note that in these models the atomic parameters for Fe X, Fe XI and Fe XIV come from the distorted wave calculations of Mason (1975)
- The remainder are also the results of distorted wave calculations, mainly by Blaha (1968) and Krueger & Czyzak (1970)
- More sophisticated calculations using the close-coupling method were beginning to be made at this time as reported by Mason (1994) in her critical assessment of excitation data for Fe IX - Fe XIV
- A year or two before this the Iron Project was set up and made its first goal the calculation of excitation data for ground state fine structure transitions - just those seen in the Seyfert galaxy spectra
- Between 1994 and 1997, new collision strengths with a detailed treatment of resonances became available for all the ions in the above table except Fe VII and Fe IX

- Ferguson, Korista and Ferland (1997) made some general photoionization models of Seyfert galaxies using the new improved excitation rates
- They find that emission comes from gas at a few $\times 10^4$K
- Their predictions are compared to the observations of the Circinus galaxy below

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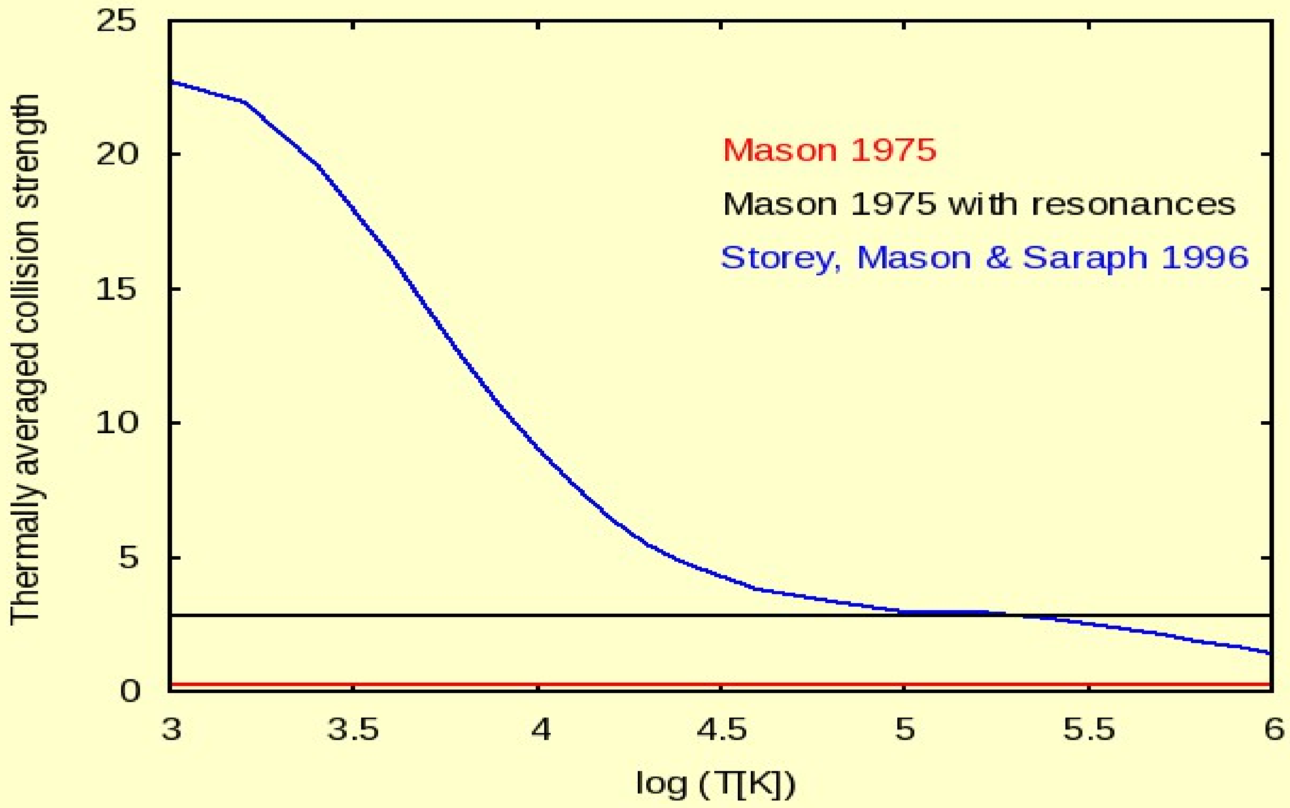
Ratio	Obs	Ferguson *et al* (1997)
[Fe X]/[S VIII]	2.4	34.
[Fe XI]/[S VIII]	1.5	1.4
[Fe XIV]/[S VIII]	$<$2.4	16.
[Fe VII]/[S VIII]	1.3	0.74
[Si VI]/[S VIII]	2.0	3.3
[Si VII]/[S VIII]	3.2	3.9
[S IX]/[S VIII]	1.0	5.0
[Ca VIII]/[S VIII]	1.5	5.3

- Agreement between the model predictions and theory is worse with some large differences
- The differences for Fe X and Fe XIV are particularly large
- Ferguson *et al* estimate that the abundance of Fe would have to be reduced by an order of magnitude relative to other elements to get agreement for these ions
- There is no physical reason to expect such a result and they question the accuracy of the calculated excitation cross-sections

Theoretical work on the Fe XIV ${}^2\mathbf{P}^{\rm o}_{1/2}$ - ${}^2\mathbf{P}^{\rm o}_{3/2}$ transition

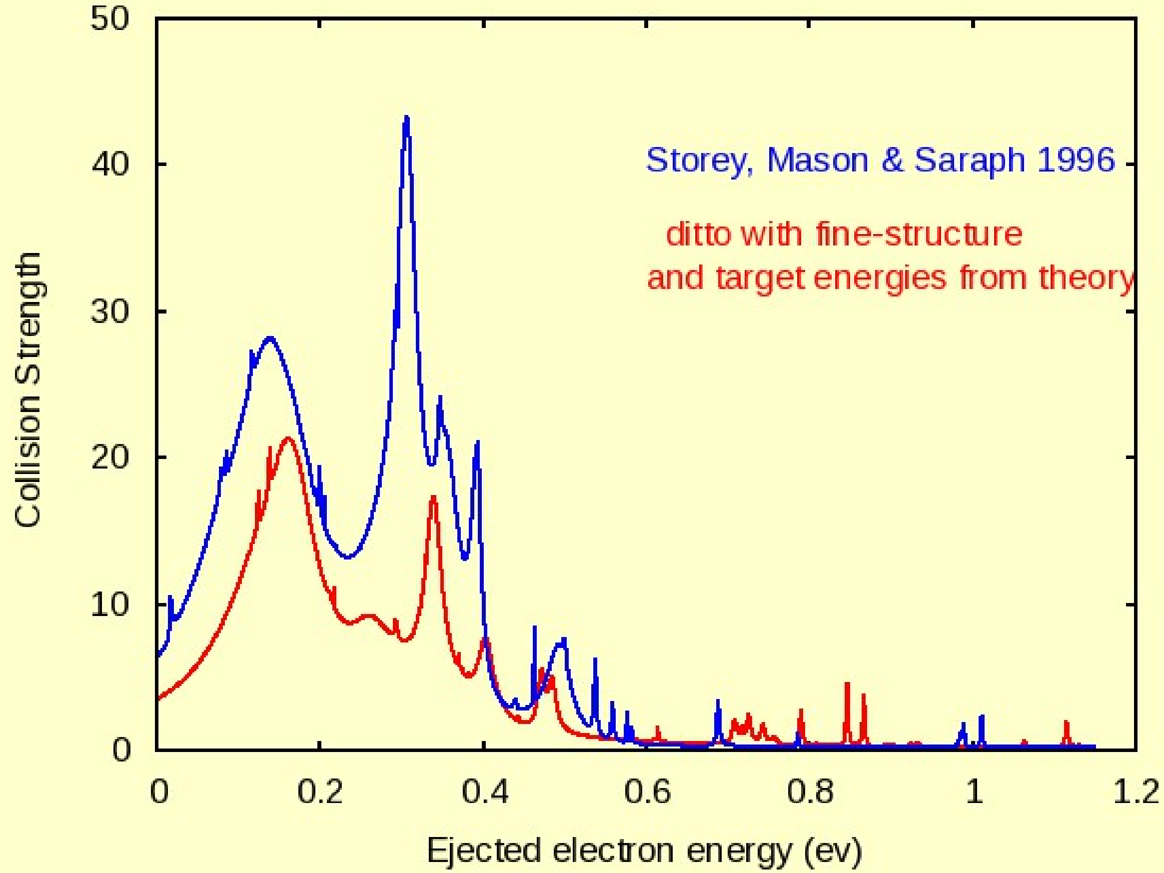
- How accurate are the near threshold excitation data (collision strengths) for these ions?
- The collision strengths used by Ferguson *et al* for direct excitation of the the $\lambda 5303$ transition is from Storey, Mason and Saraph (1996)



Current state of theory

- Two new and very elaborate calculations of collision strengths for Fe^{13+} exist
- Tayal, (ApJS, **178**, 359, 2008) use the Breit-Pauli R-matrix approach in a 135-level calculation, including some n=4 states
- Liang *et al* (ApJS, in press) made a 197-level calculation, using the R-matrix approach with the intermediate coupling frame transformation method. Excitation to n=4 is also included plus some correlation
- Before discussing their results examine the near threshold resonances in more detail

- Results of two new R-matrix Breit-Pauli calculations using the same target wave functions as Storey, Mason & Saraph (1996)



- The large value of the thermally averaged collision strength at $\approx 10^4$K is due to the near threshold group of resonances

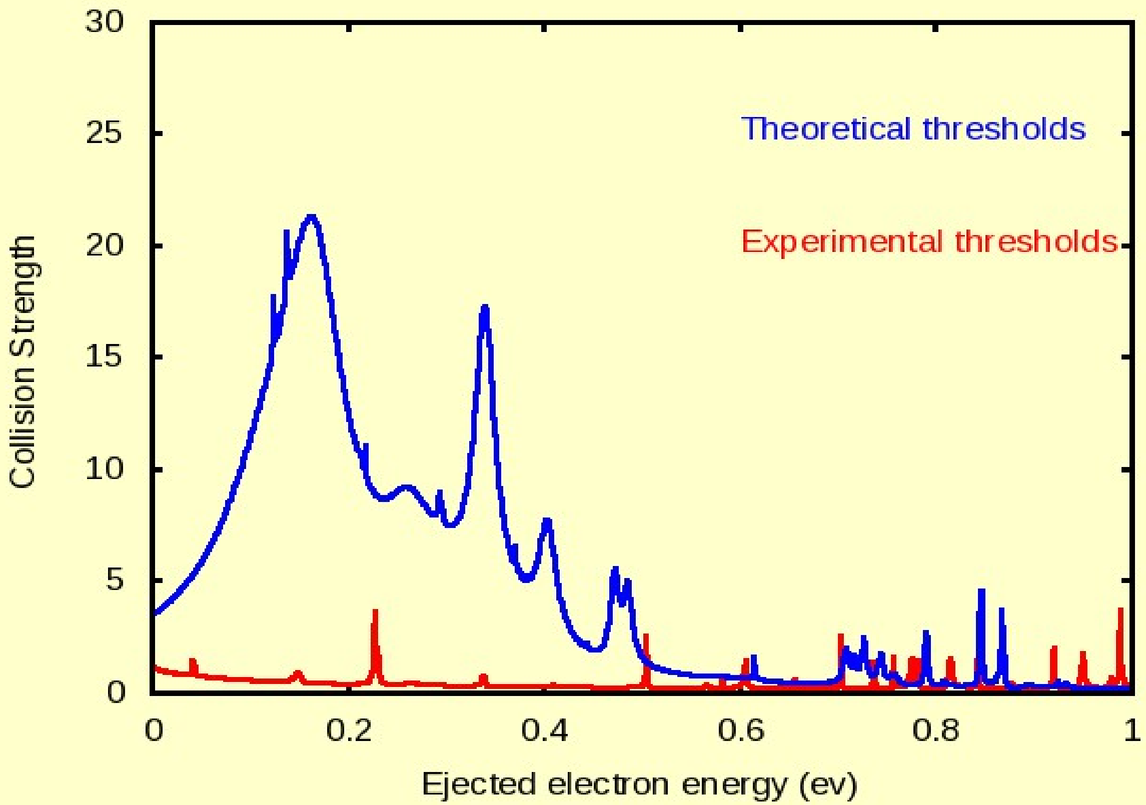
- Analysis shows that the large resonance features are n=7 Rydberg states with relatively high angular momentum, attached to the **tenth** target level, which is **3s3p**^{2} ^{2}**P**$_{3/2}$

$J\pi$	nl	Energy (eV)	ν_{10}
2^e	7g	0.120	6.9820
3^e	7g	0.032	6.9755
		0.134	6.9830
		0.236	6.9906
4^o	7h	0.216	6.9891
		0.532	7.0126
4^e	7g	0.235	6.9905
	7i	0.341	6.9984

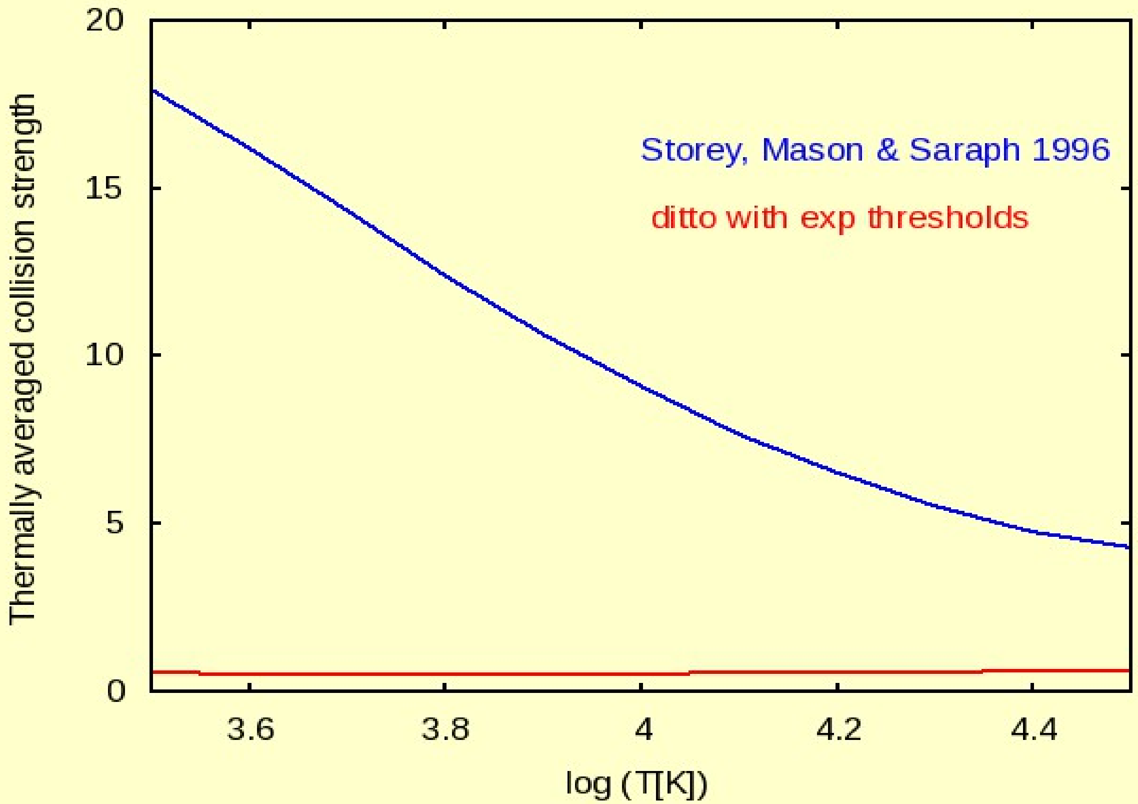
etc

- The key point is that states with $l = 4, 5, 6$ have effective quantum numbers very close to the integer value and almost exclusively with $\nu_{10} < 7$
- We can expect that theory will position them very accurately relative to the relevant threshold
- This would not necessarily be so for low l states

- The two new large scale calculations referred to above both use theoretical target energies for the thresholds
- However, both calculations place the tenth level **too high** by about 0.04 Ryd or 0.5eV
- If we return to the updated Storey *et al* (1996) calculation but adjust the target energies to the experimentally known ones



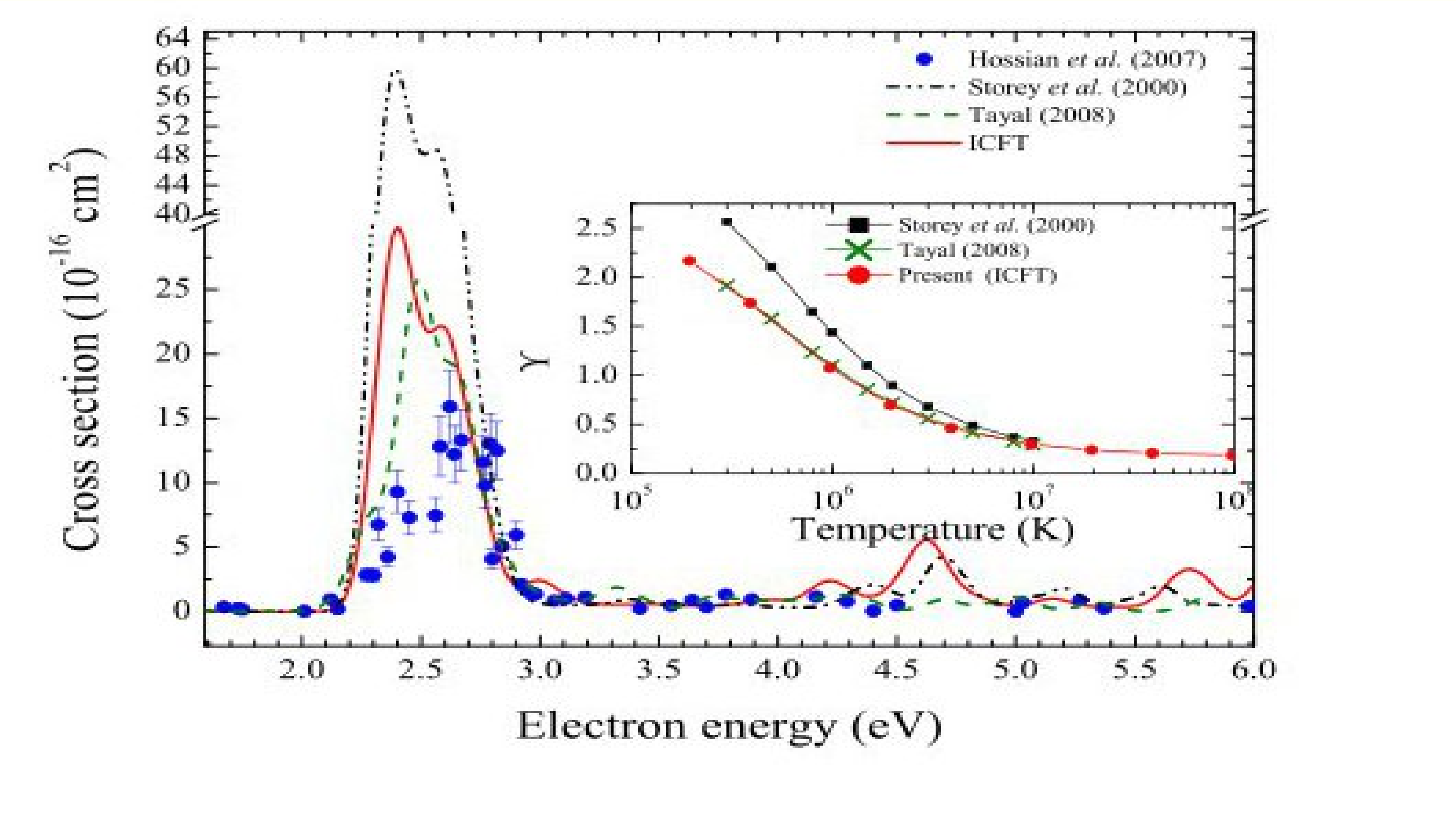
- The 0.5eV downward correction to the $3s3p^2\ ^2P_{3/2}$ threshold causes the whole $n = 7$ resonance group to fall below the $^2P^o_{3/2}$ level in the elastic scattering region
- The thermally averaged collision strength falls to ≈ 0.7 between $10^4 - 10^5$K



Latest theory compared to experiment

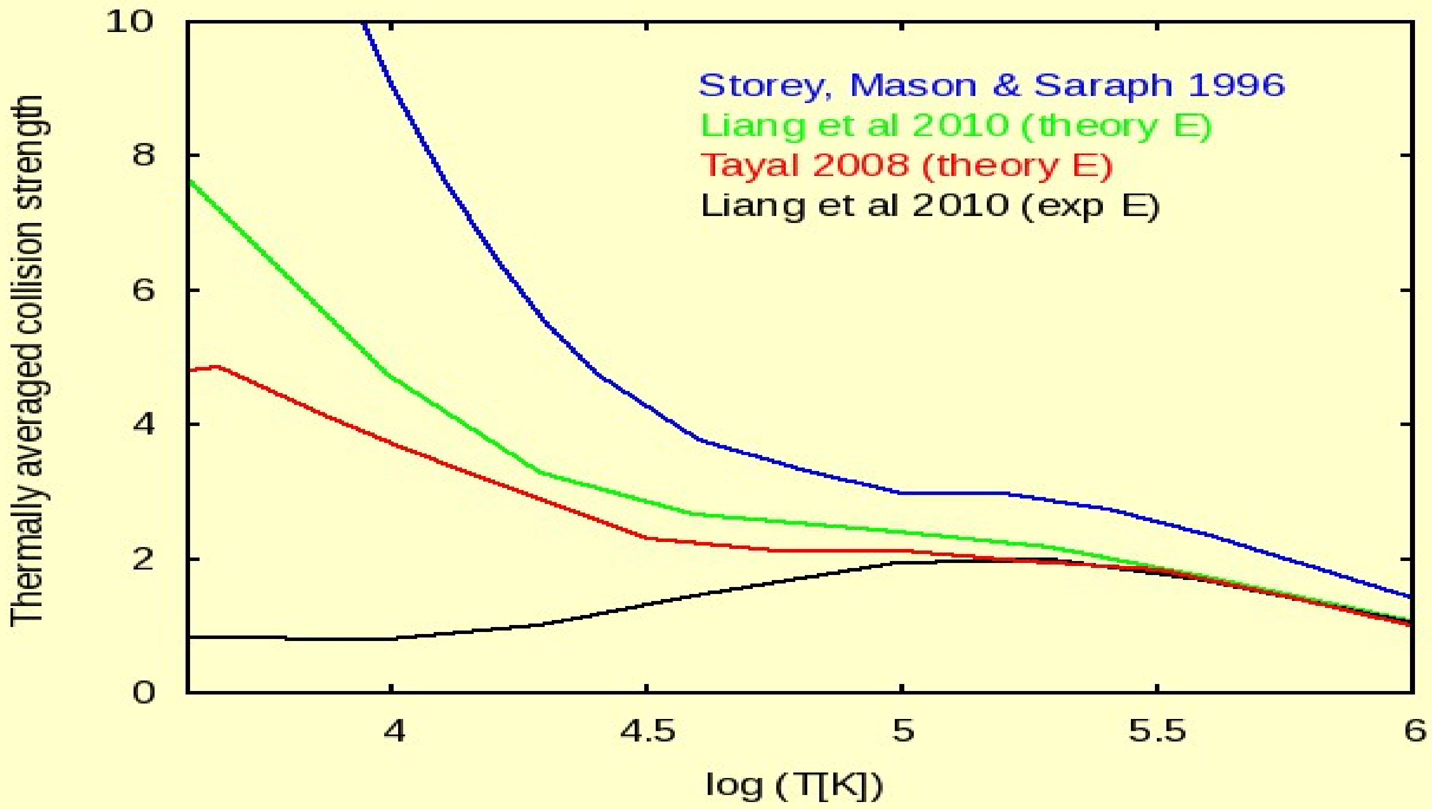
- Measurements of the near threshold cross-section have recently been made by Hossain *et al* (Phys. Rev. A, **75**, 022709, 2007)

- Cross-section can be converted to collision strength approximately by dividing by 2.2 at the position of the peak



Thermally averaged collision strengths

- The figure shows thermally averaged collision strengths from Tayal (2008) and Liang *et al* (2010) with theoretical threshold energies and with experimental threshold energies, all compared to the Storey *et al* 1996 results used in the Seyfert analysis of Ferguson *et al* 1997.



Summary

- Large scale R-matrix calculations using **theoretical** thresholds broadly agree with experiment for the Fe XIV $^2P^o_{1/2}$ - $^2P^o_{3/2}$ near threshold collision strength
- Using **experimental** threshold energies pushes the near threshold resonances below the $^2P^o_{3/2}$ level in marked disagreement with experiment
- The resulting thermally averaged collision strengths are a better match to the Seyfert models
- At present theory, observation and experiment cannot be reconciled
- Empirical uncertainty in theory - Storey, Mason & Saraph, 30% at 10^6K, factor 10 at 10^4K. Latest theory results agree at 10^6K, factor five at 10^4K
- A rather extreme case but with the best current theory *ab initio* thresholds (and resonance series) are uncertain at the 0.5eV level